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The Importance of Coupling Factor for Underwater Acoustic Projectors

Presented at the 127th Meeting of the Acoustical Society of America, June 1994, Cambridge, Massachusetts

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PREFACE

The work presented in this document was sponsored by the Office of Naval Research and was presented as an invited paper at a special session on Transducers (Underwater Projectors) at the 127th meeting of the Acoustical Society of America.

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THE IMPORTANCE OF COUPLING FACTOR FOR UNDERWATER ACOUSTIC PROJECTORS

INTRODUCTION

Underwater sound projectors are usually operated near a resonance frequency in order to radiate high power at a reasonable efficiency. The width of the resonance peak is inversely proportional to the mechanical quality factor, Q_m, and therefore the bandwidth of a projector is often said to be determined by Q_m. However, an equally important parameter affecting the bandwidth is the effective coupling factor, k_{eff}. The connection between bandwidth and coupling factor, although expressed by Warren P. Mason in 1948, has not been generally appreciated by transducer designers and users. Recently, however, Dennis Stansfield [*Underwater Electroacoustic Transducers,* Bath U. Press and Inst. of Acoust., Bath UK, 1990] has elucidated this connection, showing explicitly how power amplifier and projector properties combine to determine practical bandwidth limitations. If the acoustic output of the projector is field-limited (i.e., by a maximum allowable drive field), the effective coupling factor furnishes a useful design starting point. Knowledge of typical values for k_{eff} for various transducer classes permits initial sizing of the transducer active material.

The Importance of Coupling Factor for Underwater Acoustic Projectors

- Definition
- How to measure
- Usefulness
  - as design starting point
  - as measure of potential bandwidth
- Examples

VIEWGRAPH 1: OUTLINE

This is a joint effort with Bill Marshall, and he is here to answer the questions that no doubt will arise during the course of the talk.

After defining the coupling factor, we will talk briefly about how it is measured, and why it is useful. For a given type of projector, one can often guess a reasonable value that will serve as a starting point for a new design. But even more important than that, the coupling factor serves as a measure of the maximum attainable bandwidth. We will give some examples to show how that works.

References

- R. S. Woollett, "Effective Coupling Factor of Single-Degree-of-Freedom Transducers," J. Acoust. Soc. Am. Vol. 40, 1966, pp. 1112-1123

- D. Stansfield, *Underwater Electroacoustic Transducers,* Bath University Press and Institute of Acoustics, UK, 1990, Chapter 5, "Bandwidth."

VIEWGRAPH 2: REFERENCES

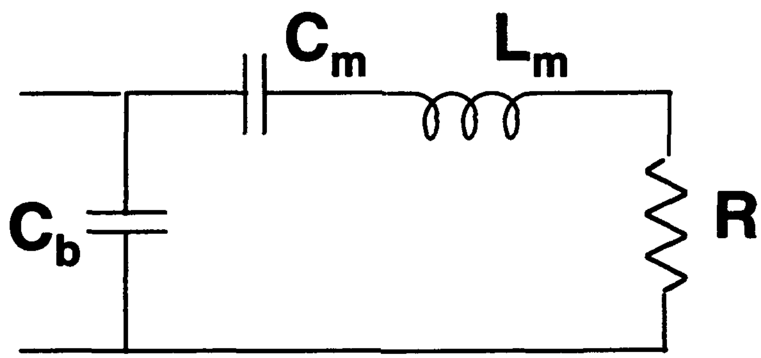
R. S. Woollett, "Effective Coupling Factor of Single-Degree-of-Freedom Transducers," *J. Acoust. Soc. Am.* vol. 40, 1966, pp. 1112-1123.

This article covers the definition and measurement of the effective coupling factor for piezoelectric, magnetostrictive, electrostatic, variable reluctance, and moving-coil transducers. In this talk, we'll confine ourselves to low-frequency, lumped-element, piezoelectric transducers. Generalization to other types is straightforward.

D. Stansfield, *Underwater Electroacoustic Transducers*, Bath University Press and Institute of Acoustics, UK, 1990, Chapter 5 "Bandwidth."

The connection between effective coupling factor and bandwidth was alluded to in some of Ralph Woollett's writings, but was only made clear to me when I read Dennis Stansfield's book a couple of years ago. His chapter on bandwidth goes into more detail than I can present here, but I recommend it highly for anyone who is interested in this subject.

Canonical Equivalent Circuit



$$k_{eff}^2 = C_m / (C_m + C_b)$$

$$Q = 2\pi\, f_0\, L_m / R$$

$$f_0 = 1 / [\, 2\pi\, (C_m\, L_m)^{1/2}]$$

VIEWGRAPH 3: CANONICAL EQUIVALENT CIRCUIT

This is the equivalent circuit that Ralph Woollett called the canonical equivalent circuit for a resonant, piezoelectic transducer. It is the simplest equivalent circuit that adequately describes the behavior of a piezoelectric transducer in the vicinity of a resonance.

The series-RLC resonant branch, consisting of the capacitance, C_m, the inductance, L_m, and the resistance, R, is the motional branch, i.e., due to the electromechanical coupling. The shunt capacitance, C_b, is the blocked capacitance, i.e., the capacitance measured if the motion could be prevented by clamping. Since it is impossible to clamp most underwater projectors, this quantity turns out to be the most difficult of the circuit parameters to measure. Luckily, we do have ways to get at it.

The equivalent circuit shows the basic elements of a piezoelectric projector radiating underwater sound. The resistive load, R, includes the radiation resistance and any mechanical losses in the transducer mechanism. The motional inductance, L_m, arises from the mass of the resonator, including the radiation mass. The motional capacitance, C_m, comes from its compliance.

The coupling factor (squared) is defined as the ratio of the mechanical energy resulting from the applied drive voltage to the electrical energy input. Thus it can be simply expressed as

$$k_{eff}^2 = \frac{C_m}{C_m + C_b},$$

because at resonance, the energy stored in the mechanical side is

$$\frac{1}{2} C_m \times \text{(applied-voltage-squared)},$$

while the total input energy is

$$\frac{1}{2} (C_m + C_b) \times \text{(applied-voltage-squared)}.$$

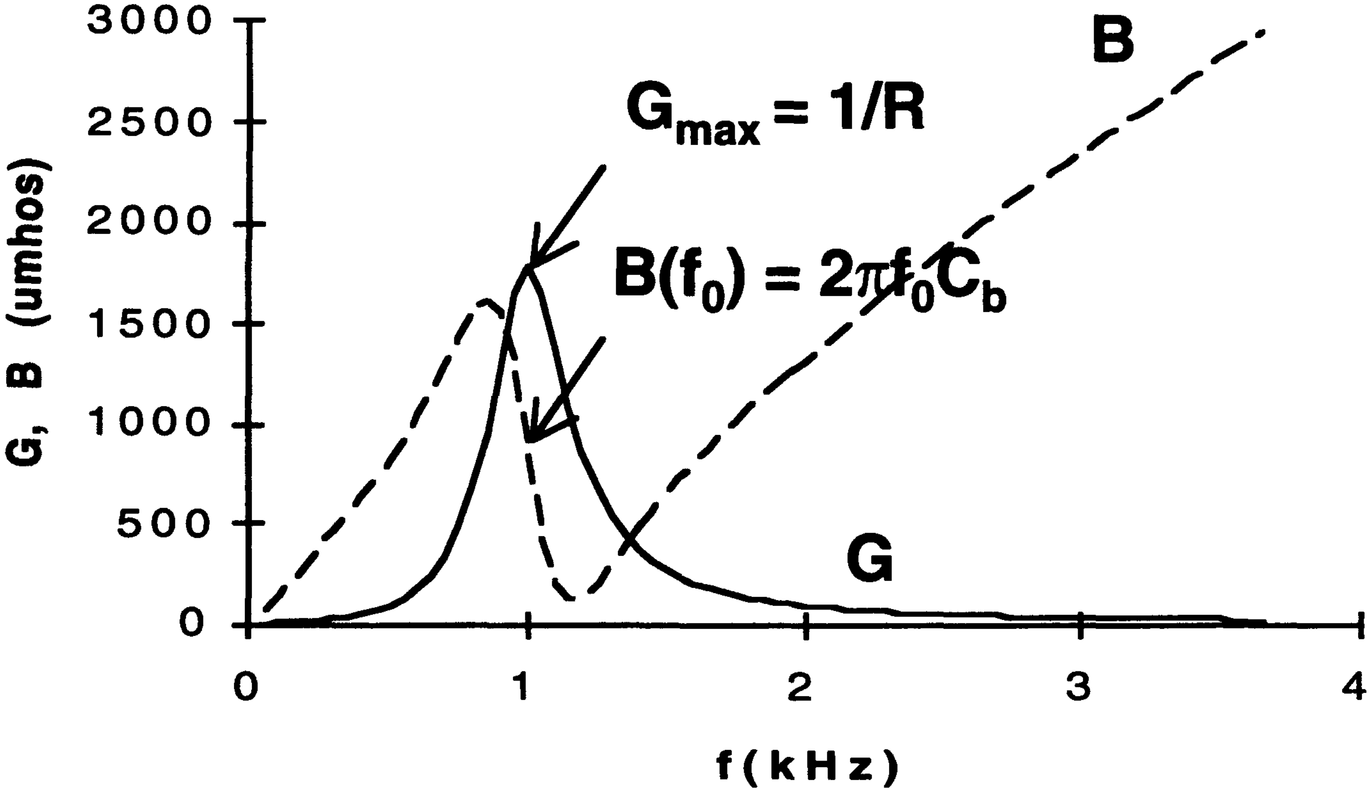
Only mechanical compliances, not masses, can be calculated under static conditions.

When we talk about coupling factor, we distinguish between the material coupling factor (of the piezoelectric or magnetostrictive material *per se*) and the effective coupling factor (of the transducer as a whole).

Maximum k_{eff} is that of the basic piezoelectric material for a piezoelectric or magnetostrictive transducer, unity for moving-coil, electrostatic, or variable-reluctance transducer. For transducers that can be unstable, like electrostatic and parallel-field variable-reluctance transducers (the gap can snap shut and stay there if the bias field is too high) k_{eff} greater than unity would represent instability. For moving coil devices k_{eff} can never be greater than unity, but it can get close (loudspeakers have $k_{eff} \sim 0.98$).

We will be talking about the mechanical quality factor, Q, a great deal. It is defined as the ratio of the reactance to the resistance at resonance. The resonance frequency is inversely proportional to the square root of the motional LC product.

Admittance, $Y = G + jB$



VIEWGRAPH 4: ADMITTANCE, $Y = G + jB$

The complex admittance of the canonical equivalent circuit consists of the conductance, G, and the susceptance, B. At resonance, the conductance goes through a peak, which we call G_{max}. The mechanical quality factor, Q, is related to the width of the conductance peak at the half-conductance points. The susceptance goes through a maximum and then a minimum in the vicinity of the resonance, passing through $2\pi f_0 C_b$ at resonance. At very low frequencies, the susceptance is that of the free capacitance, $C_m + C_b$. At well above resonance, it becomes that of the blocked capacitance, C_b.

How to Measure k_{eff}

$Q > 50$

$k_{eff}^2 = 1 - (f_0 / f_{anti})^2$

f_0 = resonance frequency

f_{anti} = antiresonance frequency

$50 > Q > 10$

$k_{eff}^2 = (1 + QQ_e)^{-1}$

$Q = f_0 / (f_2 - f_1)$

$G(f_1) = G(f_2) = G_{max}/2$

$Q_e = B(f_0)/G_{max}$

VIEWGRAPH 5: HOW TO MEASURE k_{eff}

Free and blocked capacitances -- a nice theory but difficult in practice. If you try to measure at very low and very high frequencies, you may have a different equivalent circuit to contend with. Better practice to make all measurements near the resonance frequency of interest. However, measurements are much easier for air (vs. water) loading, where losses are small.

The |Y| vs. f method described by Gordon Martin is useful because the equipment required is readily available. The calculations, however, are very complicated unless $Q > 50$.

The Y=G+jB vs. f method requires the measurement of real and imaginary parts of the admittance, but such equipment is now widely available, and the calculations are simple.

If $Q > 50$:

Measure resonance frequency, f_0, the frequency of maximum G, i.e., G_{max}.

Measure antiresonance frequency, f_{anti}, the frequency of maximum resistance.

$$k_{eff}^2 = 1 - \left(\frac{f_0}{f_{anti}}\right)^2.$$

If $50 > Q > 10$:

$$k_{eff}^2 = \frac{1}{(1 + QQ_e)},$$

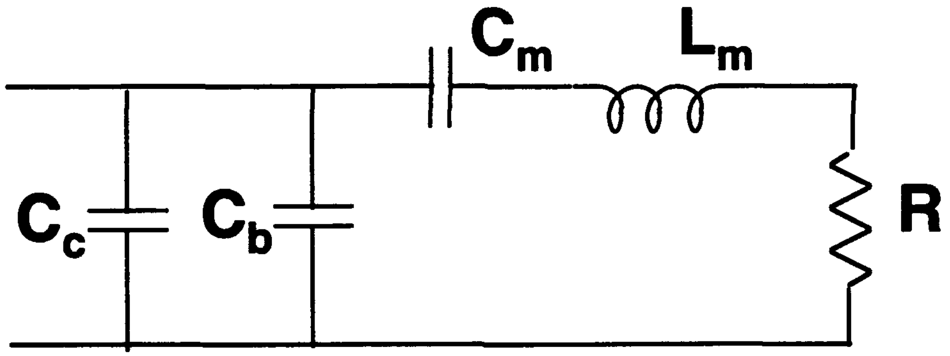
Measure $Q = \frac{f_0}{f_2 - f_1}$, where

$$G(f_1) = G(f_2) = \frac{G_{max}}{2}.$$

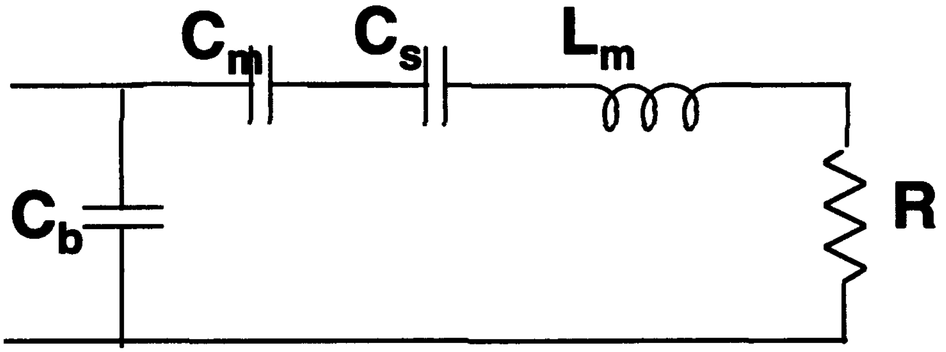
Measure $Q_e = \frac{B(f_0)}{G_{max}}$.

Conditions That Degrade k_{eff}

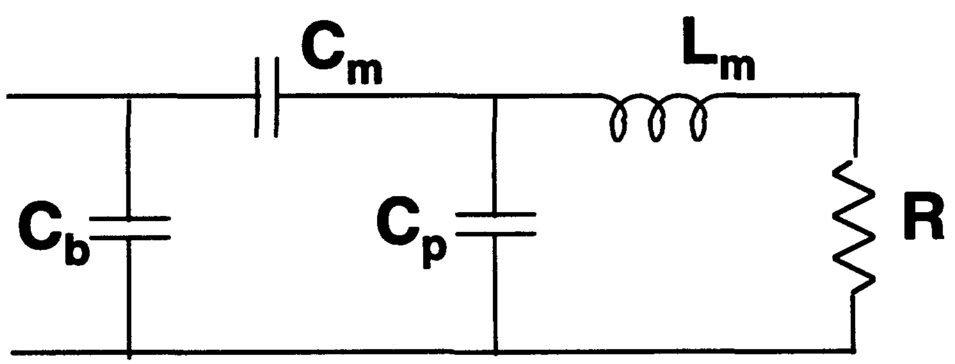
- long cable (adds to C_b): $k_{eff}^2 = C_m/(C_c+C_b+C_m)$



- stress rod: $k_{eff}^2 = C_m/[C_b(1+C_m/C_s)+C_m]$



- glue joints: $k_{eff}^2 = [C_m/(C_m+C_p)][C_m/(C_b+C_m)]$



VIEWGRAPH 6: CONDITIONS THAT DEGRADE k_{eff}

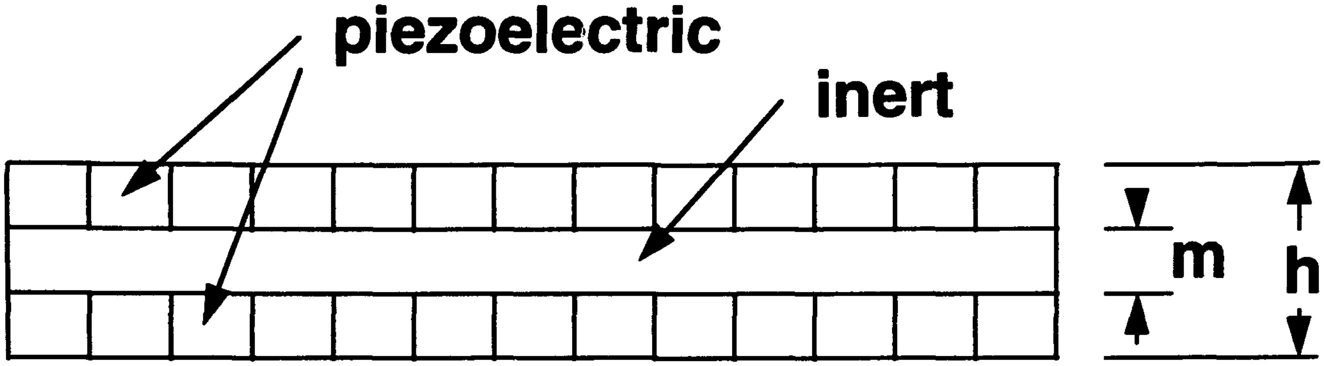
Anything that increases C_b, such as adding a cable, degrades the coupling.

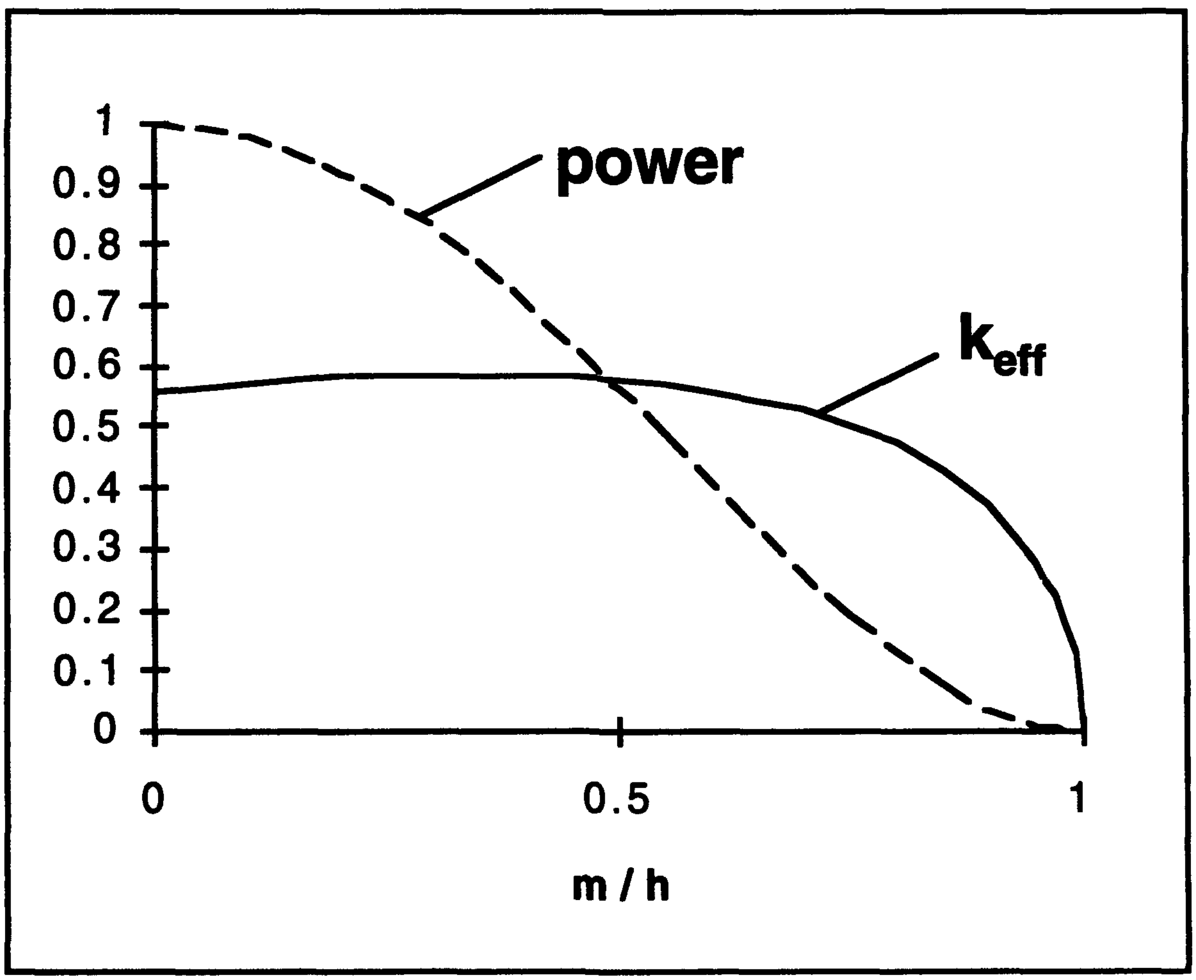
The smaller the motional C, the smaller k_{eff} becomes. Because we are stuck with compliance of material, C_m, any additional series compliance, C_s, such as that of a prestress rod, will act to degrade coupling because it decreases the mechanical compliance (i.e., stiffens the transducer).

Glue joints in a stack of piezoelectric plates increase the compliance of the stack, but because they store mechanical energy outside of the piezoelectric transduction material, they cause a reduction in the coupling.

Conditions That Improve k_{eff}

- **partial excitation of bender bar to create more uniform stress field**





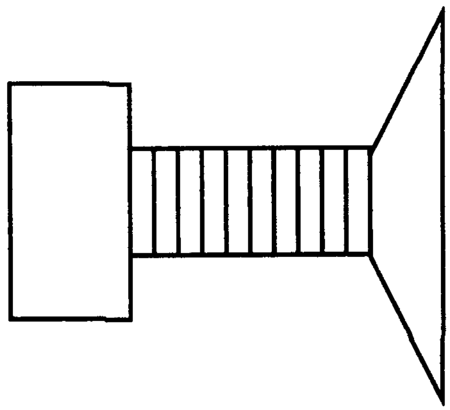
VIEWGRAPH 7: CONDITIONS THAT IMPROVE k_{eff}

There exists methods you can use to improve the coupling factor, and one of them is illustrated here. This is a bender bar transducer, consisting of two outer layers of piezoelectric material that act as a bimorph (i.e., one layer expands while the other layer contracts). By removing the piezoelectric material from a central core, and replacing it with an inert material that has the same modulus, the effective coupling can be increased somewhat because the stress field within the active, piezoelectric material is rendered more uniform. Only the highly stressed regions are piezoelectrically driven. The maximum coupling occurs when the core thickness is one-third of the total thickness. Because we have a smaller volume of piezoelectric material, however, the power-handling capability of the bar is reduced, this can be seen in the plot that shows both the effective coupling factor and the power as a function of the inert-core fraction.

Two Transducer Types

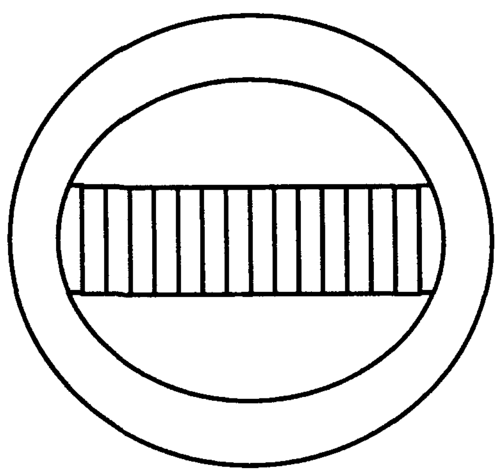
Tonpilz

$k_{eff} = 0.55$



Flextensional

$k_{eff} = 0.35$



VIEWGRAPH 8: TWO TRANSDUCER TYPES

This viewgraph is presented to illustrate typical coupling factors one encounters in practice for projectors using PZT-8, a good high-power lead zirconate titanate with material $k_{33} = 0.65$.

The tonpilz transducer uses a stack of PZT plates to drive a pistonlike head mass. A larger tail mass acts as an approximation to a rigid backing. Mass-loading lowers the frequency from the half-wavelength resonance frequency that would occur for the unloaded stack. For tonpilz typical, $k_{eff} = 0.55$.

The flextensional transducer uses a similar stack to drive an oval shell into a flexural radiating mode. Because of the compliance of the shell, the coupling factor is lower for flextensional transducers than for tonpilz projectors. For flextensional typical, $k_{eff} = 0.35$.

Volume of Piezoelectric Material

If the output power, P, is limited by a maximum allowable electric field, E_{lim}, then required volume is

$$V = P/(2\pi\ f_0\ \eta_{ma} Q\ u_{lim}\ k_{eff}^2)$$

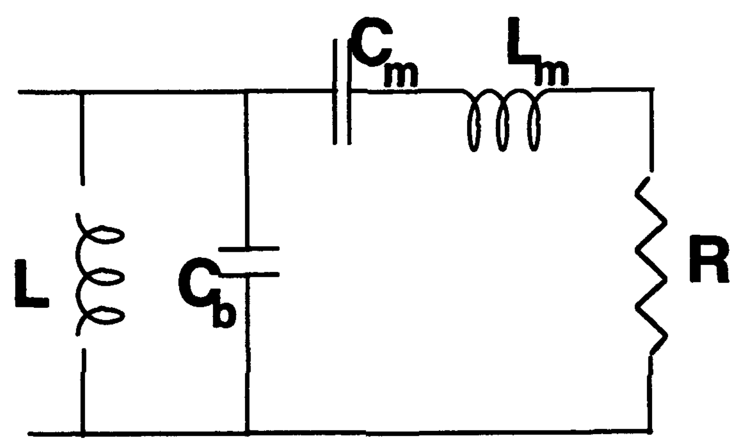
where

f_0 = resonance frequency
η_{ma} = mechanoacoustic efficiency
Q = mechanical quality factor
$u_{lim} = (1/2)\ \varepsilon^T E_{lim}^2$
ε^T =free permittivity
k_{eff} = effective coupling factor

VIEWGRAPH 9: VOLUME OF PIEZOELECTRIC MATERIAL

When the output power is limited by some maximum allowable electric field strength, E_{lim} (e.g., 10 Vrms/mil for PZT-8) as is often the case for high-power low-Q projectors, the required volume of piezoelectric material is easily estimated from this equation, which is often used as a starting point in projector design. We need to have a good estimate of the effective coupling factor because the volume is proportional to the inverse square of k_{eff}.

Parallel Tuning

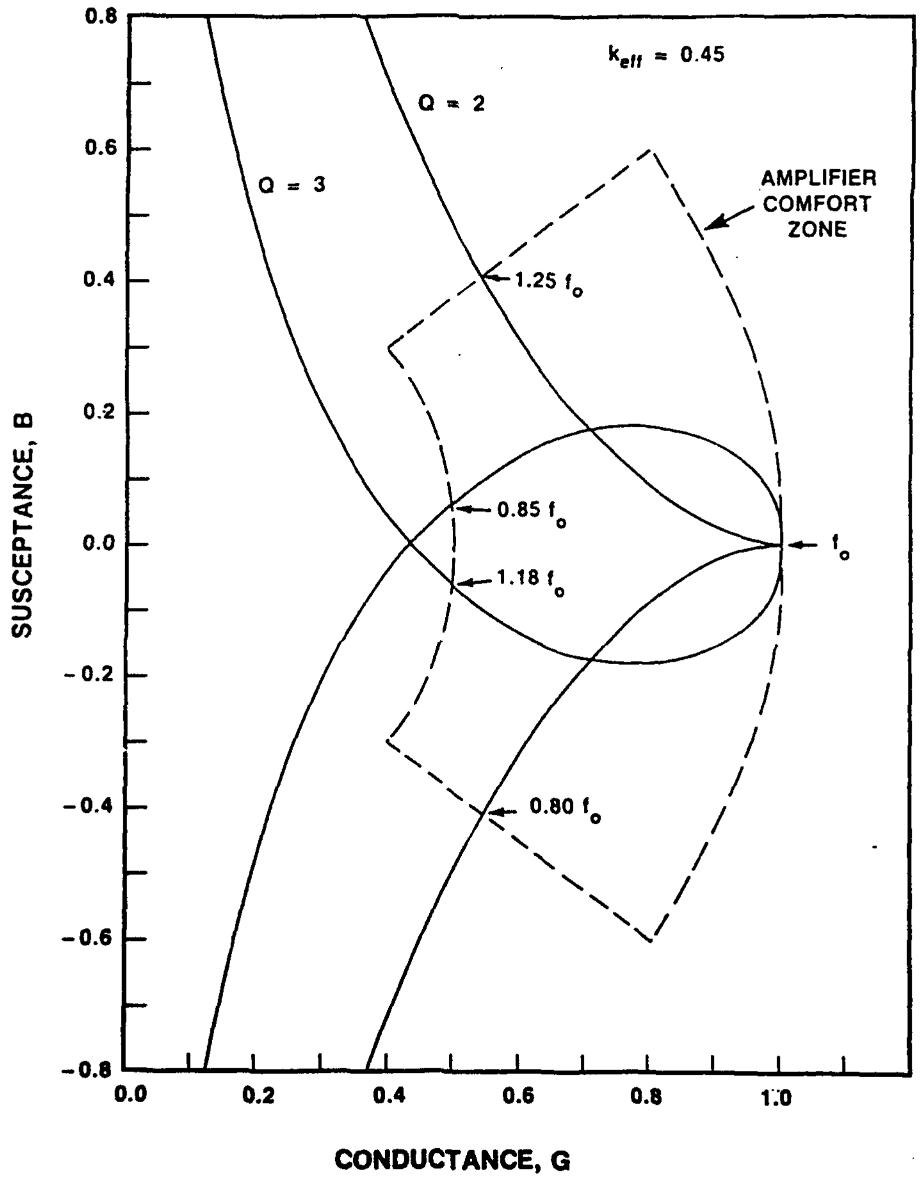


$$L = 1/\,(2\pi\, f_0)^2\, C_b$$

VIEWGRAPH 10: PARALLEL TUNING

Now I want to talk about the relationship between the effective coupling factor and the bandwidth you can get out of a projector. In what follows we will assume that the transducer is tuned so as to present a resistive load to the amplifier at resonance. The tuning will be done with a parallel inductor which will resonate with the blocked capacitance at the mechanical resonance frequency. In other words, right at the resonance frequency, the parallel combination presents negligible admittance, while the motional reactance vanishes and the transducer simply reduces to a single load resistance, R.

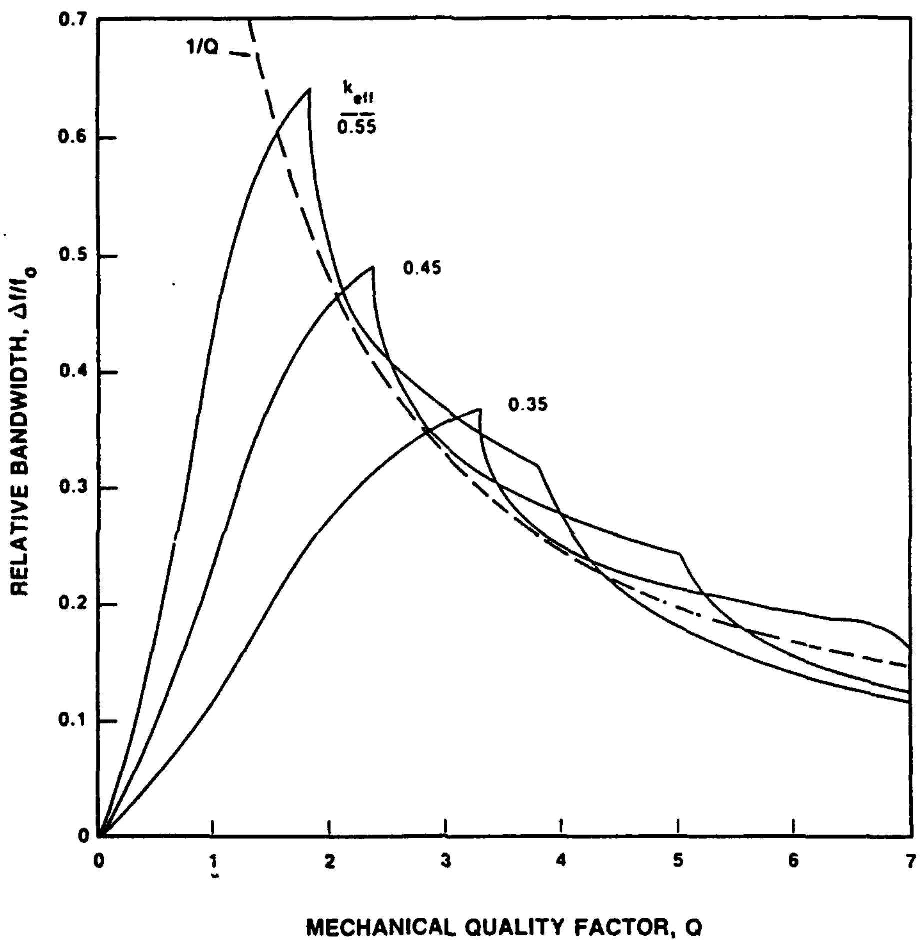
AMPLIFIER REQUIREMENTS



VIEWGRAPH 11: AMPLIFIER REQUIREMENTS

What requirements does the amplifier impose on the transducer designer? Here is a plot, in the complex plane, of the admittance loop of a parallel-tuned transducer that, in this example, has an effective coupling factor of 0.45. Two loops are shown, one having a Q of 2, the other with a Q of 3. Stansfield's approach is to define the practical operating band as involving no more than a two-to-one variation in the magnitude of the admittance and no more than a plus-or-minus 37-degree variation in the phase angle. (The latter requirement corresponds to an 80 percent power factor.) These limits are represented by the dashed box, labeled the "amplifier comfort zone." You can see that, for the Q of 3, the admittance loop enters and leaves the box across the half-magnitude boundaries, whereas the lower-Q loop crosses the constant-phase boundaries. Thus, there is an optimum value of Q, about two and one-half in this case, for which the loop will enter and leave the box in the vicinity of the corners. That loop would represent the largest bandwidth, because it would spend "more time" inside the amplifier comfort zone.

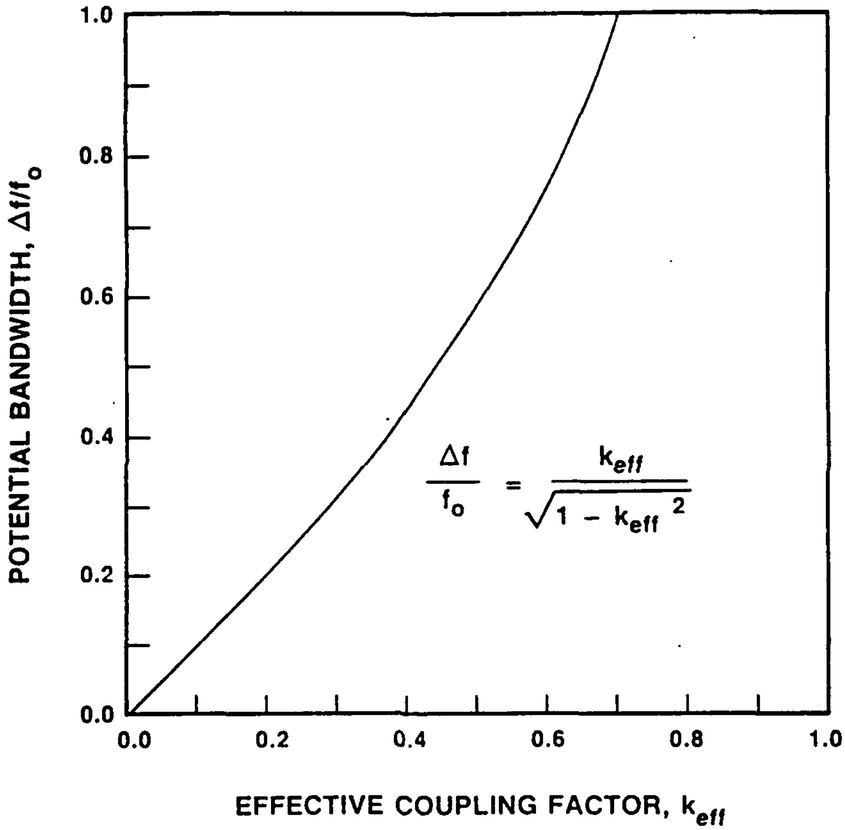
BANDWIDTH IS NOT ALWAYS 1/Q



VIEWGRAPH 12: BANDWIDTH IS NOT ALWAYS 1/Q

These are plots of the bandwidth determined by the Stansfield criterion for three different values of the effective coupling factor, k_{eff}. For coupling factor, you could read transducer type, with 0.55 representing a tonpilz transducer and 0.35 representing a typical flextensional transducer. If we look, for a moment, at the middle plot, we see that a Q of about 2.5 does indeed give us the maximum bandwidth that can be obtained (almost 50 percent) from a transducer whose k_{eff} is 0.45. If we want more bandwidth, we will need a higher effective coupling factor, either by going to a tonpilz design or by using a material with a larger intrinsic coupling.

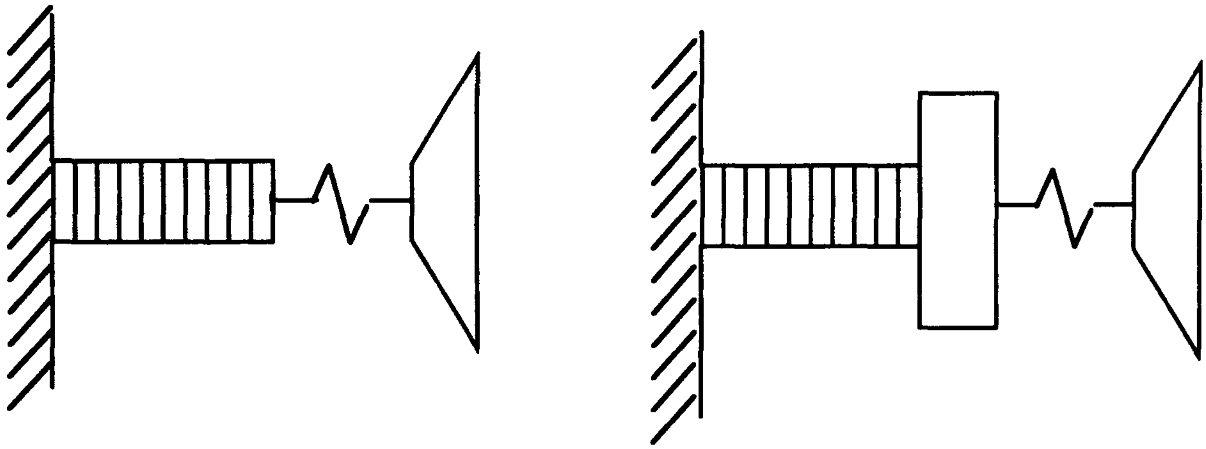
MASON'S BANDWIDTH CRITERION



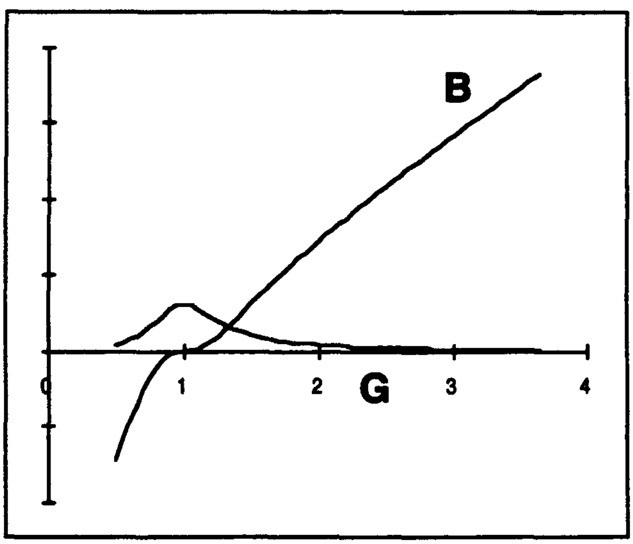
VIEWGRAPH 13: MASON'S BANDWIDTH CRITERION

The Mason criterion for the bandwidth is an estimate of the maximum practical percentage bandwidth that can be obtained with a given transducer, assuming it has been tuned and loaded optimally. This potential bandwidth is a function of the effective coupling factor of the transducer, and here is where we can understand the importance of the coupling factor. This is a plot of the Mason criterion for the potential bandwidth as a function of the effective coupling factor, k_{eff}. Since the effective coupling factor is always less than the intrinsic material coupling factor, k_{33}, we can see that, for maximum bandwidth, we need to have as high a k_{33} as possible. Lead zirconate titanate (PZT) and Terfenol-D both have k_{33}'s in the neighborhood of 0.65. In order to be competitive in the bandwidth arena, the new electrostrictive materials should be achieving similar values, so that the transducer effective coupling factors will be comparable to those obtained with the older materials.

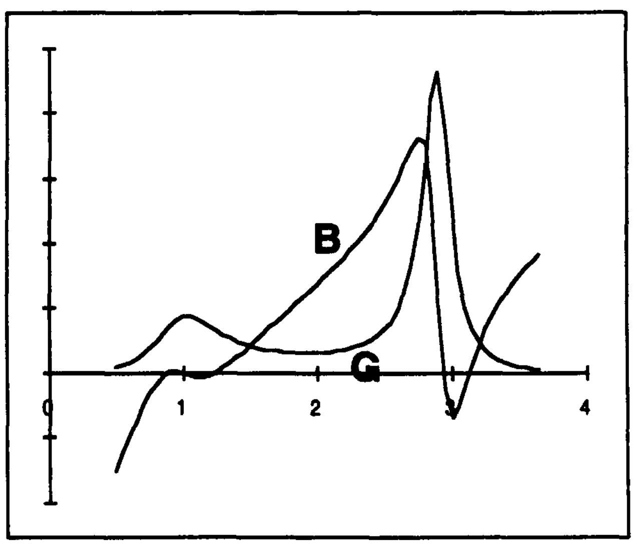
Introducing a Second Resonance



Single Resonance **Two Resonances**



F(kHz)



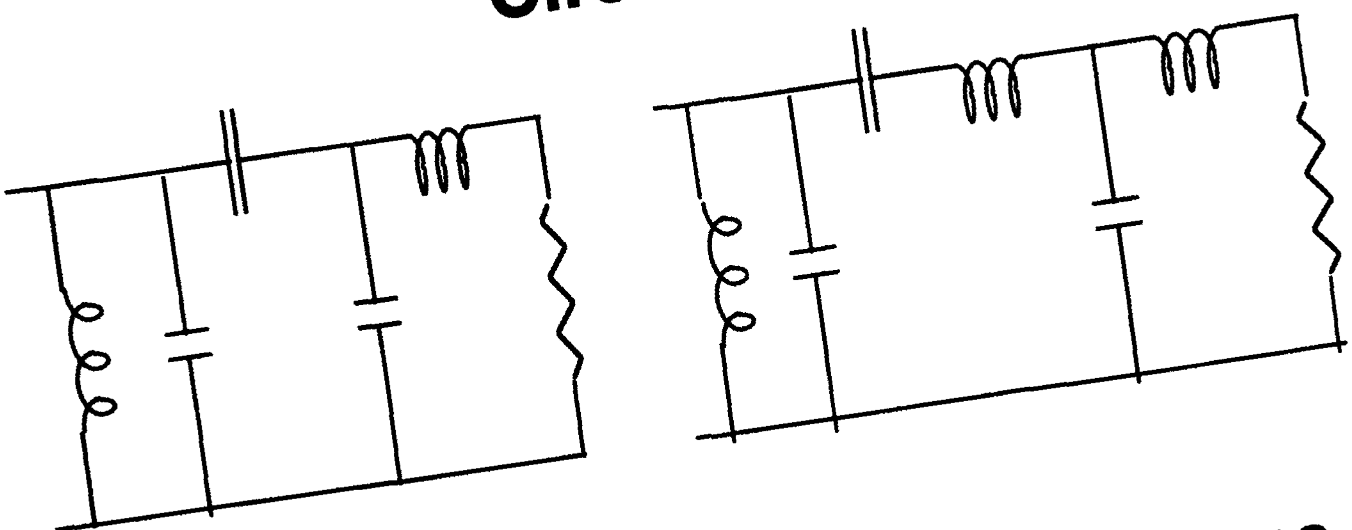
F(kHz)

VIEWGRAPH 14: INTRODUCING A SECOND RESONANCE

Another way to increase the coupling factor is by introducing a second resonance. Steve Thompson, of Westinghouse in Cleveland, has a patent on a doubly resonant transducer. This is also discussed by Stansfield. Here we have two tonpilz transducers. The one on the left is the conventional, singly resonant device, but it is shown with an extra spring between the driver stack and the head mass. (This spring could represent the effect of glue joints in the stack, for example.) Its presence means that the effective coupling factor is less than the material value (50 percent vs. 65 percent, in the example we discuss here).

The transducer on the right side of the viewgraph, however, has an extra mass added between the stack and the spring. This mass introduces a second resonance, and you can see that on the admittance plot at about three times the fundamental frequency. Comparing the two conductance plots, you can see that G gets lifted up by the presence of the second resonance. At the same time, the susceptance, B, is stretched out in the neighborhood of its zero crossings. Thus, the bandwidth over which B and G vary within the amplifier comfort zone is increased by the presence of the second higher resonance, even though no other use is made of it, i.e., we are not trying to operate the transducer at the higher-frequency resonance.

Two Similar Equivalent Circuits



- **Single Resonance**

$k_{mat} = 0.65$

$k_{static} = 0.50$

$k_{eff} = 0.50$

$k_{eff}/(1-k_{eff}^2)^{1/2} = 0.58$

optimum Q = 2.0

bandwidth = 0.55

- **Two Resonances**

$k_{mat} = 0.65$

$k_{static} = 0.50$

$k_{eff} = 0.57$

$k_{eff}/(1-k_{eff}^2)^{1/2} = 0.69$

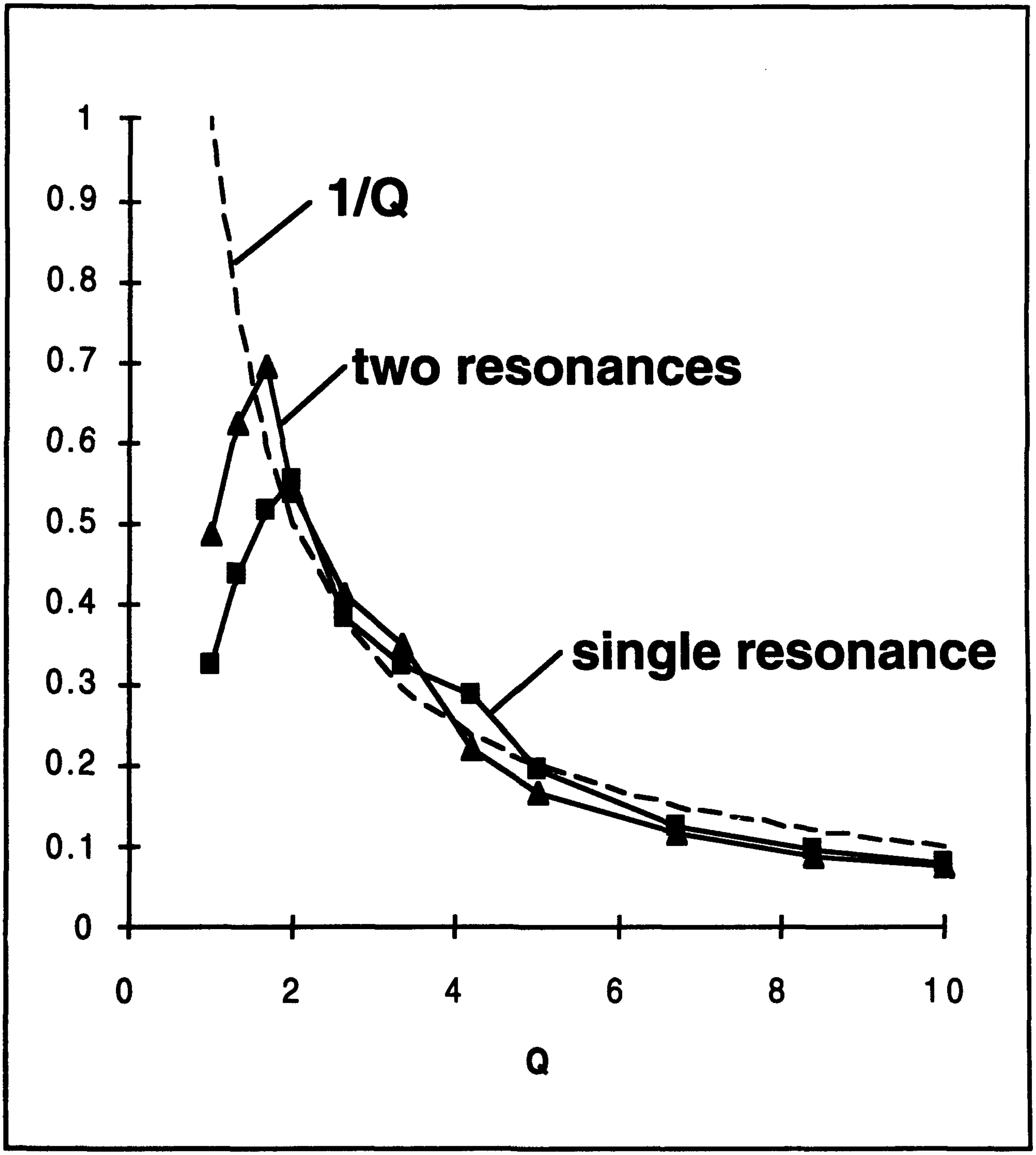
optimum Q = 1.7

bandwidth = 0.69

VIEWGRAPH 15: TWO SIMILAR EQUIVALENT CIRCUITS

In choosing the parameters for this example, I have kept all the capacitances equal for the two equivalent circuits. This means that the static coupling factors are identical (as are the underlying material coupling factors). The inductances were adjusted to produce the same fundamental resonance frequency. Then to determine the effective coupling, we made the resistance small and used the QQ_e-method. For the single-resonance case, k_{eff} is equal to the static value, 50 percent, because that circuit is reducible to the canonical type. In the double-resonant case, however, the k_{eff} is higher, 57 percent. The higher k_{eff} implies a larger obtainable bandwidth, using Mason's criterion, 69 percent vs. 58 percent. By varying the load resistance to adjust the mechanical quality factor, we could find an optimum Q, equal to 2.0 for the singly resonant device and 1.7 for the doubly resonant case. If these Q's could, in fact, be realized in practice, the resulting percentage bandwidths would be 55% for the single resonance and 69 percent for the doubly resonant device, a significant improvement provided by the second resonance.

Bandwidth vs Q for Singly and Doubly Resonant Transducers



VIEWGRAPH 16: BANDWIDTH VS. Q FOR SINGLY AND DOUBLY RESONANT TRANSDUCERS

This is the percentage bandwidth as measured by remaining within the amplifier comfort zone for the singly and doubly resonant transducers. You can see that the second resonance, and the resultant higher coupling factor allows us to get up a little higher on the 1/Q-curve to get a higher percentage bandwidth. Of course, actually accomplishing this potential bandwidth requires that we can achieve the optimum Q values. It is not that easy to make the Q come out to be what we want it to be. These values, 2.0 and 1.7, respectively, for the singly and doubly resonant cases, would probably only be achievable for elements that are part of a planar array of closely spaced elements.

Coupling factor is important for underwater acoustic projectors

- High-power projectors operate near mechanical resonance frequency
- Width of resonance peak = 1/Q
- But bandwidth is not always = 1/Q
- Mason criterion relates bandwidth to effective coupling factor:

$$\Delta f/f_0 = k_{eff}/(1-k_{eff}^2)^{1/2}$$

- Knowledge of k_{eff} helps in initial sizing of projector:

$$V = P/2\pi\, f_0\, \eta_{ma} Q\, u_{lim}\, k_{eff}^2$$

VIEWGRAPH 17: CONCLUSIONS

The effective coupling factor is important for a projector, because it determines the power and bandwidth available. Because we want high power, the projector has to operate near the mechanical resonance frequency. Although the width of the response near resonance is 1/Q, where Q is the mechanical quality factor, the bandwidth is not necessarily equal to 1/Q because of amplifier limitations. If we assume that the amplifier needs to see an admittance that is confined to a certain region in the complex plane, Mason's criterion tells us that, under the best of loading conditions, the percentage bandwidth will not exceed

$$\frac{\Delta f}{f_0} = \frac{k_{eff}}{(1 - k_{eff}^2)^{1/2}} .$$

In addition, knowledge of the effective coupling to be expected in a new design allows us to determine how much piezoelectric material we are going to need:

$$V = \frac{P}{2\pi\, f_0\, \eta_{ma}\, Qu_{lim}\, k_{eff}^2} .$$

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Edo, Salt Lake City (D. Baird)	1
FanTech (G. McMahon)	1
Georgia Institute of Technology (G. Caille, J. Caspell, G. Larson, J. Jarzynski, P. Rogers)	5
Image Acoustics (J. Butler, C. Sherman, S. Ehrlich)	3
Interface Engineering (S. Gilardi)	1
Lockheed/Sanders (R. Porzio, P. Harvey, C. Wason, G. Bernier)	4
Martin-Marietta, Baltimore (P. Kuhn)	1
Westinghouse Electric Corp., Cleveland (S. Thompson, M. Johnson)	2
Massa Products (G. Cavanagh)	1
MSI (L. Bowen)	1
Pennsylvania State University (W. Thompson)	1
Univ. of Texas, Austin (E. Hixson, D. Blackstock)	1
D. Ricketts	1
D. Stansfield	1
D. Summa	1